Fermi National Accelerator Laboratory

FERMILAB-Conf-99/208-E
D0

Subjet Multiplicity in Quark and Gluon Jets at D0

B. Abbott et al.
The D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

September 1999

Contributed paper to *EPS99 and Lepton-Photon 99*,
Tampere, Finland and Stanford, California, July 15-21, 1999 and August 9-14, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Fermilab-Conf-99/208-E

Subjet Multiplicity in Quark and Gluon Jets at DØ

The DØ Collaboration *
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(July 28, 1999)

Abstract

We measure the subjet multiplicity M in jets reconstructed with a successive combination type of jet algorithm (k_T). We select jets with $55 < E_T < 100$ GeV and $|\eta| < 0.5$. We compare similar samples of jets at $\sqrt{s} = 1800$ and 630 GeV. The HERWIG Monte Carlo simulation predicts that 59% of the jets are gluon jets at $\sqrt{s} = 1800$ GeV, and 33% at $\sqrt{s} = 630$ GeV. Using this information, we extract the subjet multiplicity in quark (M_q) and gluon (M_g) jets. We also measure the ratio $R \equiv \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04(\text{stat})^{+0.23}_{-0.19}(\text{sys})$.

*Submitted to the *International Europhysics Conference* on *High Energy Physics, EPS-HEP99*, 15 – 21 July, 1999, Tampere, Finland.

B. Abbott,[45] M. Abolins,[42] V. Abramov,[18] B.S. Acharya,[11] I. Adam,[44] D.L. Adams,[54] M. Adams,[28] S. Ahn,[27] V. Akimov,[16] G.A. Alves,[2] N. Amos,[41] E.W. Anderson,[34] M.M. Baarmand,[47] V.V. Babintsev,[18] L. Babukhadia,[20] A. Baden,[38] B. Baldin,[27] S. Banerjee,[11] J. Bantly,[51] E. Barberis,[21] P. Baringer,[35] J.F. Bartlett,[27] A. Belyaev,[17] S.B. Beri,[9] I. Bertram,[19] V.A. Bezzubov,[18] P.C. Bhat,[27] V. Bhatnagar,[9] M. Bhattacharjee,[47] G. Blazey,[29] S. Blessing,[25] P. Bloom,[22] A. Boehnlein,[27] N.I. Bojko,[18] F. Borcherding,[27] C. Boswell,[24] A. Brandt,[27] R. Breedon,[22] G. Briskin,[51] R. Brock,[42] A. Bross,[27] D. Buchholz,[30] V.S. Burtovoi,[18] J.M. Butler,[39] W. Carvalho,[3] D. Casey,[42] Z. Casilum,[47] H. Castilla-Valdez,[14] D. Chakraborty,[47] K.M. Chan,[46] S.V. Chekulaev,[18] W. Chen,[47] D.K. Cho,[46] S. Choi,[13] S. Chopra,[25] B.C. Choudhary,[24] J.H. Christenson,[27] M. Chung,[28] D. Claes,[43] A.R. Clark,[21] W.G. Cobau,[38] J. Cochran,[24] L. Coney,[32] W.E. Cooper,[27] D. Coppage,[35] C. Cretsinger,[46] D. Cullen-Vidal,[51] M.A.C. Cummings,[29] D. Cutts,[51] O.I. Dahl,[21] K. Davis,[20] K. De,[52] K. Del Signore,[41] M. Demarteau,[27] D. Denisov,[27] S.P. Denisov,[18] H.T. Diehl,[27] M. Diesburg,[27] G. Di Loreto,[42] P. Draper,[52] Y. Ducros,[8] L.V. Dudko,[17] S.R. Dugad,[11] A. Dyshkant,[18] D. Edmunds,[42] J. Ellison,[24] V.D. Elvira,[47] R. Engelmann,[47] S. Eno,[38] G. Eppley,[54] P. Ermolov,[17] O.V. Eroshin,[18] J. Estrada,[46] H. Evans,[44] V.N. Evdokimov,[18] T. Fahland,[23] M.K. Fatyga,[46] S. Feher,[27] D. Fein,[20] T. Ferbel,[46] H.E. Fisk,[27] Y. Fisyak,[48] E. Flattum,[27] G.E. Forden,[20] M. Fortner,[29] K.C. Frame,[42] S. Fuess,[27] E. Gallas,[27] A.N. Galyaev,[18] P. Gartung,[24] V. Gavrilov,[16] T.L. Geld,[42] R.J. Genik II,[42] K. Genser,[27] C.E. Gerber,[27] Y. Gershtein,[51] B. Gibbard,[48] G. Ginther,[46] B. Gobbi,[30] B. Gómez,[5] G. Gómez,[38] P.I. Goncharov,[18] J.L. González Solís,[14] H. Gordon,[48] L.T. Goss,[53] K. Gounder,[24] A. Goussiou,[47] N. Graf,[48] P.D. Grannis,[47] D.R. Green,[27] J.A. Green,[34] H. Greenlee,[27] S. Grinstein,[1] P. Grudberg,[21] S. Grünendahl,[27] G. Guglielmo,[50] J.A. Guida,[20] J.M. Guida,[51] A. Gupta,[11] S.N. Gurzhiev,[18] G. Gutierrez,[27] P. Gutierrez,[50] N.J. Hadley,[38] H. Haggerty,[27] S. Hagopian,[25] V. Hagopian,[25] K.S. Hahn,[46] R.E. Hall,[23] P. Hanlet,[40] S. Hansen,[27] J.M. Hauptman,[34] C. Hays,[44] C. Hebert,[35] D. Hedin,[29] A.P. Heinson,[24] U. Heintz,[39] R. Hernández-Montoya,[14] T. Heuring,[25] R. Hirosky,[28] J.D. Hobbs,[47] B. Hoeneisen,[6] J.S. Hoftun,[51] F. Hsieh,[41] Tong Hu,[31] A.S. Ito,[27] S.A. Jerger,[42] R. Jesik,[31] T. Joffe-Minor,[30] K. Johns,[20] M. Johnson,[27] A. Jonckheere,[27] M. Jones,[26] H. Jöstlein,[27] S.Y. Jun,[30] S. Kahn,[48] D. Karmanov,[17] D. Karmgard,[25] R. Kehoe,[32] S.K. Kim,[13] B. Klima,[27] C. Klopfenstein,[22] B. Knuteson,[21] W. Ko,[22] J.M. Kohli,[9] D. Koltick,[33] A.V. Kostritskiy,[18] J. Kotcher,[48] A.V. Kotwal,[44] A.V. Kozelov,[18] E.A. Kozlovsky,[18] J. Krane,[34] M.R. Krishnaswamy,[11] S. Krzywdzinski,[27] M. Kubantsev,[36] S. Kuleshov,[16] Y. Kulik,[47] S. Kunori,[38] F. Landry,[42] G. Landsberg,[51] A. Leflat,[17] J. Li,[52] Q.Z. Li,[27] J.G.R. Lima,[3] D. Lincoln,[27] S.L. Linn,[25] J. Linnemann,[42] R. Lipton,[27] J.G. Lu,[4] A. Lucotte,[47] L. Lueking,[27] A.K.A. Maciel,[29] R.J. Madaras,[21] R. Madden,[25] L. Magaña-Mendoza,[14] V. Manankov,[17] S. Mani,[22] H.S. Mao,[4] R. Markeloff,[29] T. Marshall,[31] M.I. Martin,[27] R.D. Martin,[28] K.M. Mauritz,[34] B. May,[30] A.A. Mayorov,[18] R. McCarthy,[47] J. McDonald,[25] T. McKibben,[28] J. McKinley,[42] T. McMahon,[49] H.L. Melanson,[27] M. Merkin,[17] K.W. Merritt,[27] C. Miao,[51] H. Miettinen,[54] A. Mincer,[45] C.S. Mishra,[27] N. Mokhov,[27] N.K. Mondal,[11] H.E. Montgomery,[27] M. Mostafa,[1] H. da Motta,[2] F. Nang,[20] M. Narain,[39] V.S. Narasimham,[11] A. Narayanan,[20] H.A. Neal,[41] J.P. Negret,[5] P. Nemethy,[45] D. Norman,[53] L. Oesch,[41] V. Oguri,[3] N. Oshima,[27] D. Owen,[42] P. Padley,[54] A. Para,[27] N. Parashar,[40] Y.M. Park,[12] R. Partridge,[51] N. Parua,[7] M. Paterno,[46] B. Pawlik,[15] J. Perkins,[52] M. Peters,[26] R. Piegaia,[1] H. Piekarz,[25]

Y. Pischalnikov,[33] B.G. Pope,[42] H.B. Prosper,[25] S. Protopopescu,[48] J. Qian,[41] P.Z. Quintas,[27] R. Raja,[27] S. Rajagopalan,[48] O. Ramirez,[28] N.W. Reay,[36] S. Reucroft,[40] M. Rijssenbeek,[47] T. Rockwell,[42] M. Roco,[27] P. Rubinov,[30] R. Ruchti,[32] J. Rutherfoord,[20] A. Sánchez-Hernández,[14] A. Santoro,[2] L. Sawyer,[37] R.D. Schamberger,[47] H. Schellman,[30] J. Sculli,[45] E. Shabalina,[17] C. Shaffer,[25] H.C. Shankar,[11] R.K. Shivpuri,[10] D. Shpakov,[47] M. Shupe,[20] R.A. Sidwell,[36] H. Singh,[24] J.B. Singh,[9] V. Sirotenko,[29] P. Slattery,[46] E. Smith,[50] R.P. Smith,[27] R. Snihur,[30] G.R. Snow,[43] J. Snow,[49] S. Snyder,[48] J. Solomon,[28] X.F. Song,[4] M. Sosebee,[52] N. Sotnikova,[17] M. Souza,[2] N.R. Stanton,[36] G. Steinbrück,[50] R.W. Stephens,[52] M.L. Stevenson,[21] F. Stichelbaut,[48] D. Stoker,[23] V. Stolin,[16] D.A. Stoyanova,[18] M. Strauss,[50] K. Streets,[45] M. Strovink,[21] A. Sznajder,[3] P. Tamburello,[38] J. Tarazi,[23] M. Tartaglia,[27] T.L.T. Thomas,[30] J. Thompson,[38] D. Toback,[38] T.G. Trippe,[21] P.M. Tuts,[44] V. Vaniev,[18] N. Varelas,[28] E.W. Varnes,[21] A.A. Volkov,[18] A.P. Vorobiev,[18] H.D. Wahl,[25] J. Warchol,[32] G. Watts,[51] M. Wayne,[32] H. Weerts,[42] A. White,[52] J.T. White,[53] J.A. Wightman,[34] S. Willis,[29] S.J. Wimpenny,[24] J.V.D. Wirjawan,[53] J. Womersley,[27] D.R. Wood,[40] R. Yamada,[27] P. Yamin,[48] T. Yasuda,[27] P. Yepes,[54] K. Yip,[27] C. Yoshikawa,[26] S. Youssef,[25] J. Yu,[27] Y. Yu,[13] M. Zanabria,[5] Z. Zhou,[34] Z.H. Zhu,[46] M. Zielinski,[46] D. Zieminska,[31] A. Zieminski,[31] V. Zutshi,[46] E.G. Zverev,[17] and A. Zylberstejn[8]

(DØ Collaboration)

[1]Universidad de Buenos Aires, Buenos Aires, Argentina
[2]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[3]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[4]Institute of High Energy Physics, Beijing, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Universidad San Francisco de Quito, Quito, Ecuador
[7]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[8]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[9]Panjab University, Chandigarh, India
[10]Delhi University, Delhi, India
[11]Tata Institute of Fundamental Research, Mumbai, India
[12]Kyungsung University, Pusan, Korea
[13]Seoul National University, Seoul, Korea
[14]CINVESTAV, Mexico City, Mexico
[15]Institute of Nuclear Physics, Kraków, Poland
[16]Institute for Theoretical and Experimental Physics, Moscow, Russia
[17]Moscow State University, Moscow, Russia
[18]Institute for High Energy Physics, Protvino, Russia
[19]Lancaster University, Lancaster, United Kingdom
[20]University of Arizona, Tucson, Arizona 85721
[21]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[22]University of California, Davis, California 95616
[23]University of California, Irvine, California 92697
[24]University of California, Riverside, California 92521

[25]Florida State University, Tallahassee, Florida 32306
[26]University of Hawaii, Honolulu, Hawaii 96822
[27]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[28]University of Illinois at Chicago, Chicago, Illinois 60607
[29]Northern Illinois University, DeKalb, Illinois 60115
[30]Northwestern University, Evanston, Illinois 60208
[31]Indiana University, Bloomington, Indiana 47405
[32]University of Notre Dame, Notre Dame, Indiana 46556
[33]Purdue University, West Lafayette, Indiana 47907
[34]Iowa State University, Ames, Iowa 50011
[35]University of Kansas, Lawrence, Kansas 66045
[36]Kansas State University, Manhattan, Kansas 66506
[37]Louisiana Tech University, Ruston, Louisiana 71272
[38]University of Maryland, College Park, Maryland 20742
[39]Boston University, Boston, Massachusetts 02215
[40]Northeastern University, Boston, Massachusetts 02115
[41]University of Michigan, Ann Arbor, Michigan 48109
[42]Michigan State University, East Lansing, Michigan 48824
[43]University of Nebraska, Lincoln, Nebraska 68588
[44]Columbia University, New York, New York 10027
[45]New York University, New York, New York 10003
[46]University of Rochester, Rochester, New York 14627
[47]State University of New York, Stony Brook, New York 11794
[48]Brookhaven National Laboratory, Upton, New York 11973
[49]Langston University, Langston, Oklahoma 73050
[50]University of Oklahoma, Norman, Oklahoma 73019
[51]Brown University, Providence, Rhode Island 02912
[52]University of Texas, Arlington, Texas 76019
[53]Texas A&M University, College Station, Texas 77843
[54]Rice University, Houston, Texas 77005

I. INTRODUCTION

The Tevatron proton-antiproton collider is a rich environment for studying high energy physics. The dominant process is jet production, described in Quantum Chromodynamics (QCD) by scattering of the elementary quark and gluon constituents of the incoming hadron beams. In leading order (LO) QCD, there are two partons in the initial and final states of the elementary process. A jet is associated with the energy and momentum of each final state parton. Experimentally, however, a jet is a cluster of energy in the calorimeter. Understanding jet structure is the motivation for the present analysis. QCD predicts that gluons radiate more than quarks. Asymptotically, the ratio of objects within gluon jets to quark jets is expected to be in the ratio of their color charges $C_A/C_F = 9/4$ [1].

II. THE k_T JET ALGORITHM

We define jets in the DØ detector [2] with the k_T algorithm [3]. The jet algorithm starts with a list of energy preclusters, formed from calorimeter cells or from particles in a Monte Carlo event generator. The preclusters are separated by $\Delta\mathcal{R} = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.2$, where η and ϕ are the pseudorapidity and azimuthal angle of the preclusters. The steps of the jet algorithm are:

1. For each object i in the list, define $d_{ii} = E^2_{T,i}$, where E_T is the energy transverse to the beam. For each pair (i, j) of objects, also define $d_{ij} = min(E^2_{T,i}, E^2_{T,j})\frac{\Delta\mathcal{R}^2_{ij}}{D^2}$, where D is a parameter of the jet algorithm.

2. If the minimum of all possible d_{ii} and d_{ij} is a d_{ij}, then replace objects i and j by their 4-vector sum and go to step 1. Else, the minimum is a d_{ii} so remove object i from the list and define it to be a jet.

3. If any objects are left in the list, go to step 1.

The algorithm produces a list of jets, each separated by $\Delta\mathcal{R} > D$. For this analysis, $D = 0.5$.

The subjet multiplicity is a natural observable of a k_T jet [4,5]. Subjets are defined by rerunning the k_T algorithm starting with a list of preclusters in a jet. Pairs of objects with the smallest d_{ij} are merged successively until all remaining $d_{ij} > y_{cut}E^2_T(jet)$. The resolved objects are called subjets, and the number of subjets within the jet is the subjet multiplicity M. The analysis in this article uses a single resolution parameter $y_{cut} = 10^{-3}$.

III. JET SELECTION

In LO QCD, the fraction of final state jets which are gluons decreases with $x \sim E_T/\sqrt{s}$, the momentum fraction of initial state partons within the proton. For fixed E_T, the gluon jet fraction decreases when $\sqrt{s}$ is decreased from 1800 GeV to 630 GeV. We define gluon and quark enriched jet samples with identical cuts in events at $\sqrt{s} = 1800$ and 630 GeV to reduce experimental biases and systematic effects. Of the two highest E_T jets in the event, we select jets with $55 < E_T < 100$ GeV and $|\eta| < 0.5$.

IV. QUARK AND GLUON SUBJET MULTIPLICITY

There is a simple method to extract a measurement of quark and gluon jets on a statistical basis, using the tools described in the previous sections. M is the subjet multiplicity in a mixed sample of quark and gluon jets. It may be written as a linear combination of subjet multiplicity in gluon and quark jets:

$$M = fM_g + (1-f)M_q \tag{1}$$

The coefficients are the fractions of gluon and quark jets in the sample, f and $(1-f)$, respectively. Consider Eq. (1) for two similar samples of jets at $\sqrt{s} = 1800$ and 630 GeV, assuming M_g and M_q are independent of $\sqrt{s}$. The solutions are

$$M_q = \frac{f^{1800}M^{630} - f^{630}M^{1800}}{f^{1800} - f^{630}} \tag{2}$$

$$M_g = \frac{\left(1-f^{630}\right)M^{1800} - \left(1-f^{1800}\right)M^{630}}{f^{1800} - f^{630}} \tag{3}$$

where M^{1800} and M^{630} are the experimental measurements in the mixed jet samples at $\sqrt{s} = 1800$ and 630 GeV, and f^{1800} and f^{630} are the gluon jet fractions in the two samples. The method relies on knowledge of the two gluon jet fractions.

V. RESULTS

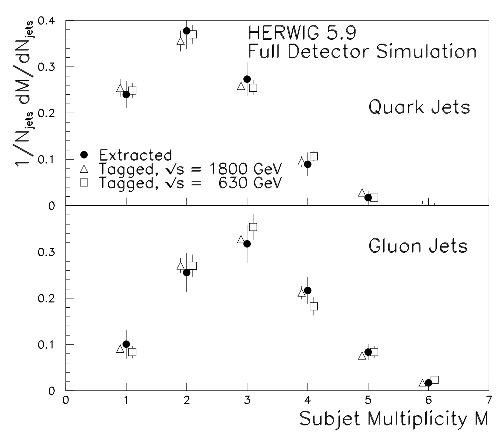

FIG. 1. Raw subjet multiplicity in fully simulated Monte Carlo quark and gluon jets. For visibility, we shift the open symbols horizontally.

The HERWIG 5.9 [6] Monte Carlo event generator provides an estimate of the gluon jet fractions. The method is tested using the detector simulation and CTEQ4M PDF. We tag every selected jet in the detector as either quark or gluon by the identity of the nearer (in $\eta \times \phi$ space) final state parton in the QCD 2-to-2 hard scatter. Fig. 1 shows that gluon jets in the detector simulation have more subjets than quark jets. The tagged subjet multiplicity distributions are similar at the two center of mass energies, verifying the assumptions in § IV.

We count tagged gluon jets and find $f^{1800} = 0.59 \pm 0.02$ and $f^{630} = 0.33 \pm 0.03$, where the uncertainties are estimated from different gluon PDF's. The nominal gluon jet fractions and the Monte Carlo measurements at $\sqrt{s} = 1800$ and 630 GeV are used in Eqs. (2-3). The extracted quark and gluon jet distributions in Fig. 1 agree with the tagged distributions and demonstrate closure of the method.

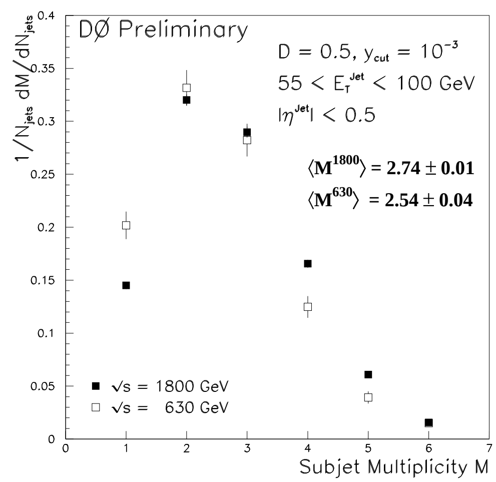

FIG. 2. Raw subjet multiplicity in jets from DØ data at $\sqrt{s} = 1800$ and 630 GeV.

Figure 2 shows the raw subjet multiplicity in DØ data at $\sqrt{s} = 1800$ GeV is higher than at $\sqrt{s} = 630$ GeV. This is consistent with the prediction that there are more gluon jets at $\sqrt{s} = 1800$ GeV compared to $\sqrt{s} = 630$ GeV, and gluons radiate more than quarks. The combination of the distributions in Fig. 2 and the gluon jet fractions gives the raw subjet multiplicity distributions in quark and gluon jets, according to Eqs. (2-3).

The quark and gluon raw subjet multiplicity distributions need separate corrections for various detector-dependent effects. These are derived from Monte Carlo, which describes the raw DØ data well. Each Monte Carlo jet in the detector simulation is matched (within $\Delta\mathcal{R} < 0.5$) to a jet reconstructed from particles without the detector simulation. We tag detector jets as either quark or gluon, and study the subjet multiplicity in particle jets M^{ptcl} *vs.* that in detector jets M^{det}. The correction unsmears M^{det} to give M^{ptcl}, in bins of M^{det}. Figure 3 shows the corrected subjet multiplicity is clearly larger for gluon jets compared to quark jets.

The gluon jet fractions are the largest source of systematic error. We vary the gluon jet fractions by the uncertainties in an anti-correlated fashion at the two values of $\sqrt{s}$ to measure the effect on R. The systematic errors listed in Table I are added in quadrature to obtain the total uncertainty in the corrected ratio $R = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04(\mathrm{stat})^{+0.23}_{-0.19}(\mathrm{sys})$.

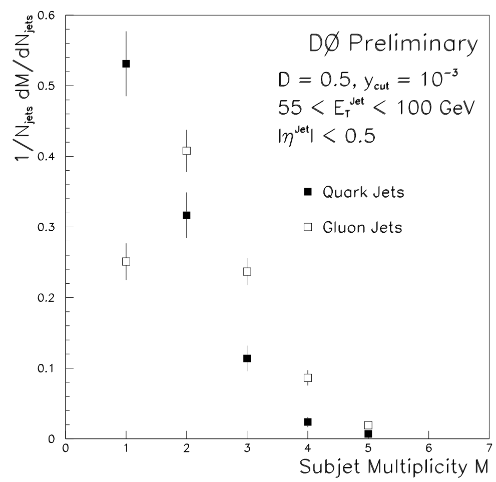

FIG. 3. Corrected subjet multiplicity in quark and gluon jets, extracted from DØ data.

TABLE I. Systematic Errors

Source	δR
Gluon Jet Fraction	$^{+0.18}_{-0.12}$
Jet E_T cut	± 0.12
Detector Simulation	± 0.08
Unsmearing	± 0.04

VI. CONCLUSION

We extract the $y_{cut} = 10^{-3}$ subjet multiplicity in quark and gluon jets from measurements of mixed jet samples at $\sqrt{s} = 1800$ and 630 GeV. On a statistical level, gluon jets have more subjets than quark jets. We measure the ratio of additional subjets in gluon jets to quark jets $R \approx 1.9 \pm 0.2$. The ratio is well described by the HERWIG parton shower Monte Carlo, and is only slightly smaller than the naive QCD prediction 9/4.

VII. ACKNOWLEDGEMENTS

We thank the Fermilab and collaborating institution staffs for contributions to this work and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

REFERENCES

[1] R.K. Ellis, W.J. Stirling, and B.R. Webber, QCD and Collider Physics, Cambridge University Press, 1996.

[2] S. Abachi *et al.*, Nucl. Instr. Meth. Phys. Res. A338 (1994) 185.

[3] S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160.

[4] S. Catani, Yu.L. Dokshitzer, and B.R. Webber, Phys. Lett. B285 (1992) 291.

[5] S. Catani, Yu.L. Dokshitzer, M.H. Seymour, B.R. Webber, Nucl. Phys. B406 (1993) 187.

[6] G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour, and L. Stanco, Comp. Phys. Comm. 67 (1992) 465.